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Evolution of a laser hybrid welding map

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Abstract

Laser arc hybrid welding combines the advantages but also the complex physical mechanisms of gas metal arc welding and laser keyhole welding. From manifold mainly experimental but also theoretical research results a map with versatile functions was initiated for the first time. The purpose is to survey the overall context and to facilitate navigation to the various phenomena that are shown through case studies accompanied by theoretical explanations and guidelines for optimization. Though not complete, the map enables systematic and graphical navigation to relevant publications. Based on a fundamental structure of the map, which was decided early, it is inherently extendable in the future by adding existing and new knowledge, also from other research groups, enabling evolution. The fundament of the map structure comprises gouge thickness, joint type and metal grade, in coherence with product and weld designers' starting points. The next hierarchy level of the map offers options in the joint type as well as in hybrid welding techniques. The latter contains techniques like double-sided welding, pulse shaping management of the arc or laser, CMT arcs, tandem arcs, or remelting of undercuts. In addition to laser-arc hybrid welding, other hybrid laser techniques like multilayer hot-wire laser welding of narrow gaps or hybrid laser friction stir welding can be taken into account. At the other end of the hierarchy, the map offers via a database-like archive electronic navigation to research results like weld macrographs, high speed imaging or numerical simulation results of the welding process.

Keywords: laser-arc hybrid welding; map; guideline; joint preparation; technique;

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1. Introduction

Laser arc hybrid welding combines a laser beam with gas metal arc welding, GMAW. Often the welding process can then benefit from the advantages from both tools, like deep penetration through the laser beam accompanied by bridging of gaps through the consumable added and melted by the electric arc process. One disadvantage is the increasing number of process parameters which requires even more knowledge and skills than the processes for a single heat source already do. Although a large amount of hybrid welding studies have been carried out during the last two decades, it is difficult to navigate to results in a systematic manner. This is a basic dilemma for laser processing and welding technology, because of the basic structure of data and information. Here methods of mapping knowledge are presented, to facilitate the optimization of the hybrid welding process.

As a study on knowledge management in the welding community has shown, despite large research and engineering efforts and experiences, for new welding applications the access to existing knowledge and data is still very difficult, Johansson et al. (2012). Basic obstacles are particularly the data structure, cultural and conservative behaviour patterns. More rational, faster access to data and knowledge for faster and better optimization of (hybrid) welding applications is desirable. Solutions on suitable mapping are scarce in welding and in laser materials processing. Interesting approaches can be found in other disciplines, e.g. in machining, Chakrabarti et al. (2007), in medicine or in bioinformatics, Ebbels et al. (2006).

Recently several new approaches were developed, tried and evaluated on how data and knowledge can be stored in a better manner, particularly by mapping, see Fig. 1.

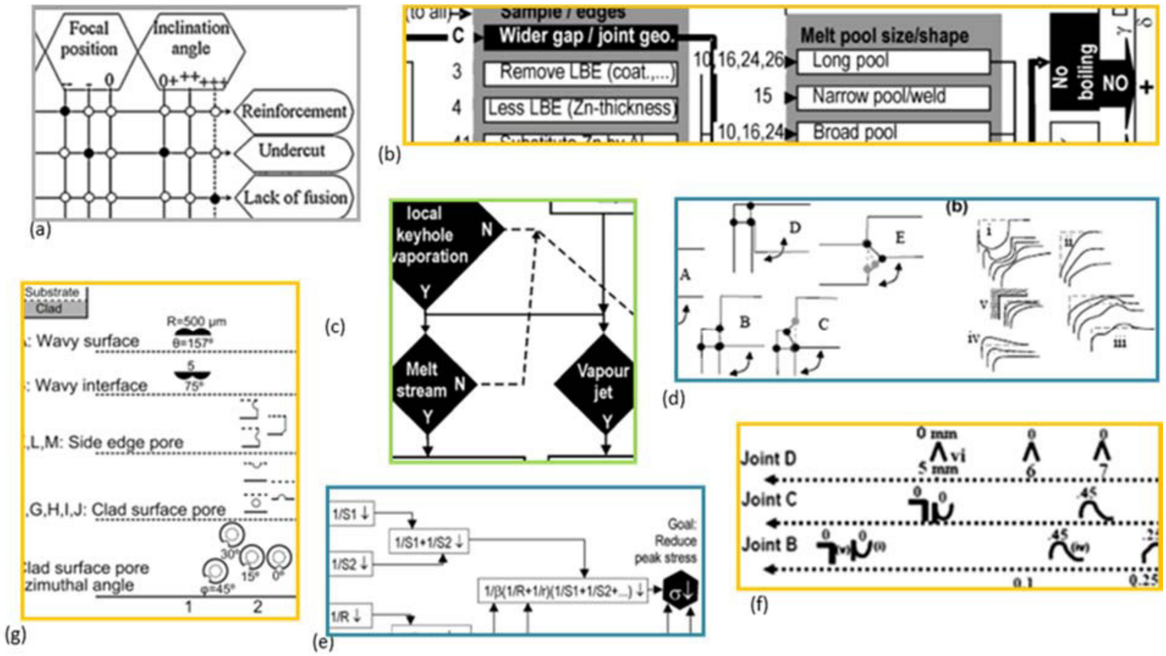

Fig.1. Different recently developed methods for improved mapping of data and knowledge on laser welding (the maps are here arranged such as to get a visual impression, not for reading the content): (a) MFC, (b),(c) BFC, (d) joint and root illustrations, (e) TFC, (f),(g) shape scale.

The Matrix Flow Chart, MFC, see Fig. 1(a), correlates for example parameter changes to desired quality improvements, Karlsson et al. (2011 I). The Bifurcation Flow Chart, BFC, was applied for all 47 publications about spatter in laser welding to connect for all cases parameters that have suppressed spatter, see Fig. 1(b), also connecting published mechanisms, Kaplan and Powell (2011). The BFC has even provided a statistical survey about confirmed trends from different sources. The bifurcation of mechanisms in a BFC that either cause or avoid spatter is shown in Fig. 1(c). Figure 1(d) visualizes the similarities of joint geometries and of root shapes and the transitions from one to another, Alam et al. (2011). A Tuning Flow Chart, TFC, Fig. 1(e), connects reduction of stress raisers to corresponding changes in weld shape parameters, Alam et al. (2011). Shapes and their key dimensions can be plotted along a scale, Fig. 1(f),(g), according to their stress raiser value, Alam et al. (2011,2013). One example of extension is the incorporation of complementary hybrid welding research results and techniques into the results and maps, from Chosun University, Korea, Bang et al. (2010 I, 2011), Joo et al. (2014).

One main limitation of these charts and maps is the limit of validity of their rules with respect to generalization, since such limit is of quantitative nature. The potential and limits of the above method examples are discussed in detail in the corresponding publications.

Here, by building on these recent experiences, further approaches have been developed, applied and analysed for laser-arc hybrid welding.

2. Methodology

Aim of the here presented approaches is to develop a suitable knowledge platform that enables continuous evolution by additional entries. During a current research project, called HYBRO (for reference see acknowledgements), along with accompanying synergy projects, a significant amount of research results have been achieved. These resulting data and knowledge shall be easily accessible, particularly for the project partners. The e-material can be divided into limited and public access rights.

The scope here comprises hybrid welding, combining any two welding techniques, though laser-arc hybrid welding is the technique most studied here.

The requirements for a hybrid welding map are specified as follows:

- Clear survey on available electronic material (from welding experiments or calculations)
- Fast navigation to electronic material
- Rules for changing welding process parameters to improve a weld quality aspect
- Explanation of physical phenomena that cause weld quality imperfections
- Generalization of the content and quantitative limits of validity

It was identified that different kinds of documentation will be required. For each approach, a hierarchy of parameters or properties of highest importance has to be early decided, typically two main parameters because of two-dimensional visualization of maps.

Mapping methods that have been developed and applied so far are

M1: Technique options map
M2: e-Archive
M3: Defect suppression catalogue
M4: MetaModel map

The differences of these mapping methods are summarized in Table 1. The technique options map, Method M1, visualizes in 2D-maps different technique options for hybrid welding. While a paramount map just shows the main combinations, accompanied by pro-/con-entries, the detailed technique options map specifies in more detail the respective technical choices and preferences, which can again be accompanied by comments. In particular, in many cases a certain joint type is associated with preferred laser or arc techniques, which is the according main hierarchy. The e-Archive, M2, is an electronic map hierarchy, starting from joint type, followed by sheet thickness and by the respective type of electronic material data (e.g. weld cross section macrographs, weld surface or root photos, high speed imaging videos, weld topology scans, etc.). A navigation map based on a subway map enables to find the entries, accompanied by a simple but consequent denomination system for all files. The navigation map for the e-Archive also shows the amount of entries per hierarchy level and e-material type. The archive is easily extendable. The Defect suppression catalogue, Method M3, is a collection of empirically or theoretically identified rules where a quality aspect was improved (usually a defect minimized or suppressed) by changing usually one process parameter. Since the rules originate from individual cases, the limits of validity are initially unknown and the increasing collection of same rules for different parameter ranges gradually widens the confirmed domain of validity. The defect suppression catalogue can be accompanied by theoretical explanations of the mechanisms behind. In contrast, the MetaModel map, M4, applies interpolating or approximating equations, e.g. high order polynomials to describe the context between e.g. a quality aspect and a number of process parameters. However, only the dependency on two of those process parameters can be visualized in a 3D-plot. MetaModel mapping is based on Design of Experiment, DoE. The advantage is that the MetaModel provides a continuum, i.e. rules throughout and their quantitative limits of validity, e.g. where the trend of a rule changes sign. The disadvantage is that the approximation involves a high level of uncertainty unless a huge number of data is available, which normally is not the case, at least not experimentally. Altogether, the four here presented methods provide complementary data, information and knowledge, as will be shown below.

Table 1: Chosen structure and standard format of the mapping methods M1-M4

Mapping method	Structure	Features / format
M1 – Technique options map	2D-map	Techniques vs. 3 main categories (joint, arc, laser)
M2 – e-Archive	Map hierarchy	Subway navigation map (joint, thickness, data)
M3 – Defect suppression catalogue	Collection	Improvement rules, cases, limits unknown
M4 – MetaModel map	3D-functions	Continuous rule extrapolation, quantitative limits

Guidelines for the use and extension of the different maps and methods are under development. It is distinguished between plain data, including electronic material, and knowledge from experts by interpreting the data to more complex explanations and guidelines. Figure 2 shows the basic framework of the hybrid welding maps under development.

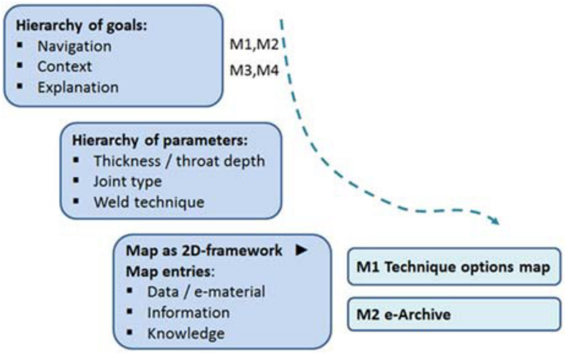

Fig. 2. Preferred basic framework and logics to develop a map, even open for evolution.

The goals of the maps for the user are navigation through data and information (on hybrid welding), understanding of the context to other information, and explanation of trends and phenomena. As the parameters of highest priority for mapping, the material (or throat) thickness and the joint type were identified, followed by the welding technique options that can be chosen. The kind of material to be entered into the maps is pure data (from experiment and simulation), e-material, information and knowledge.

3. Results and discussion

In the following, the map on hybrid welding that is under evolution will be presented (via the four methods M1-M4 mentioned above), based on its fundamental structure, examples of entries and a guideline for its use and evolution.

M1: Technique options map - to choose a hybrid welding technique

One kind of map that includes judgements is the hybrid welding *technique options map*, M1 (in contrast to plain data in the *e-archive*, M2). For a certain application to be welded, often the first decision steps, e.g. in the product design phase are about the joint design, together with the material thickness, and about the welding technique to be applied. For hybrid welding, a basic survey on welding techniques is shown in Fig. 3. It is interesting to note that the

Swedish partner, LTU, regarded hybrid welding from a laser beam combined with a second, electric heat source, while the Korean partner, CU, considered the combination of any two welding techniques, including in particular Friction Stir Welding, FSW, even combined with lasers, see Bang et al. (2010 II). Note that e.g. laser-laser would mean a technique with two laser beams, while laser-autonomous means the standard non-hybrid technique, solely with a laser, as reference. Pros and cons can be entered into the map, which pop up when pointing electronically on one hybrid combination (e.g. easily done in .pdf format via *Adobe / sticky notes*). A first choice of welding technique could be done at this level. The growth of pros and cons entries would support the evolution of such kind of map, beside the addition of further hybrid techniques. However, a good survey has to be maintained, so in case of too many extensions marking of different levels of priority is recommended.

The more detailed map on technique options is shown in Fig. 4. This map is vertically structured into three main columns, from left the joint type options, followed by options for the electric arc and by laser beam options. Suitable choice of the joint design is regarded as same important as any key arc or laser parameter and needs to be simultaneously considered. The three main categories have several options (columns) that can be chosen (multiple choices possible). The vertical dimension downwards represents increasing sheet (or weld throat) thickness, indicating which technique is more suitable for thicker material, although generalization is not always possible here. The horizontal rows represent different technique options, extendable, labelled by a letter A-H. They are marked through their letter in corresponding columns which they involve, marking with a red box the main characteristics of the respective technique. This provides a graphical profile on the different technique options that hopefully facilitates to get a survey.

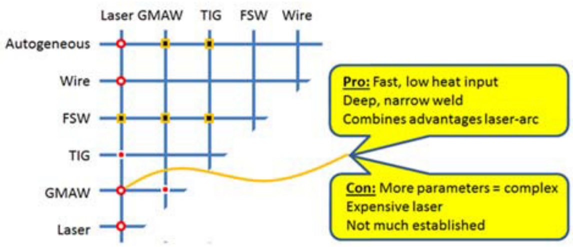

Fig. 3. Paramount map for choice the basic hybrid welding technique; red circles represent techniques studied at Luleå University of Technology, Sweden, yellow rectangles are additional hybrid (even non-laser) welding techniques studied at Chosun University, Korea, red dots are further meaningful options.

The here considered hybrid welding technique options are:

A. CMT-arc (in laser-arc hybrid welding)
B. Double-sided weld
C. Laser Metal Deposition (LMD) only to fill the gap (i.e. no arc, no keyhole, multilayer wire addition)
D. Second pass MAG only, on top of a hybrid weld (to fill deeper gaps)
E. Pulsed laser (various hypotheses why a pulsed laser can have advantages to a cw-laser)
F. Laser beam shaping in space (to optimize the keyhole behaviour in laser-arc hybrid welding)
G. Laser remelting of the hybrid weld surface to remove undercuts and to smoothen the topology
H. CO_2-laser (wavelength) instead of a fibre or disc laser, due to experiences on more robustness

As for the basic hybrid welding technique map, Fig. 3, also for the detailed technique options map, Fig. 4, comments can be added that pop up when pointing on a certain technique or aspect. Additional techniques, options and comments can be gradually entered into the map, enabling evolution. Of particular interest is to try to simultaneously or generally comment on the combination of the respective pros/cons for joint type, arc choice and laser choice. The 'technique options map' can then be connected to the e-Archive M2, via its navigation and numbering system, to track information forth and back.

The *Technique options map* has the advantage of a graphical survey on different technique options but a disadvantage is the subjective and limited comments entered while generalization of preferences can be difficult.

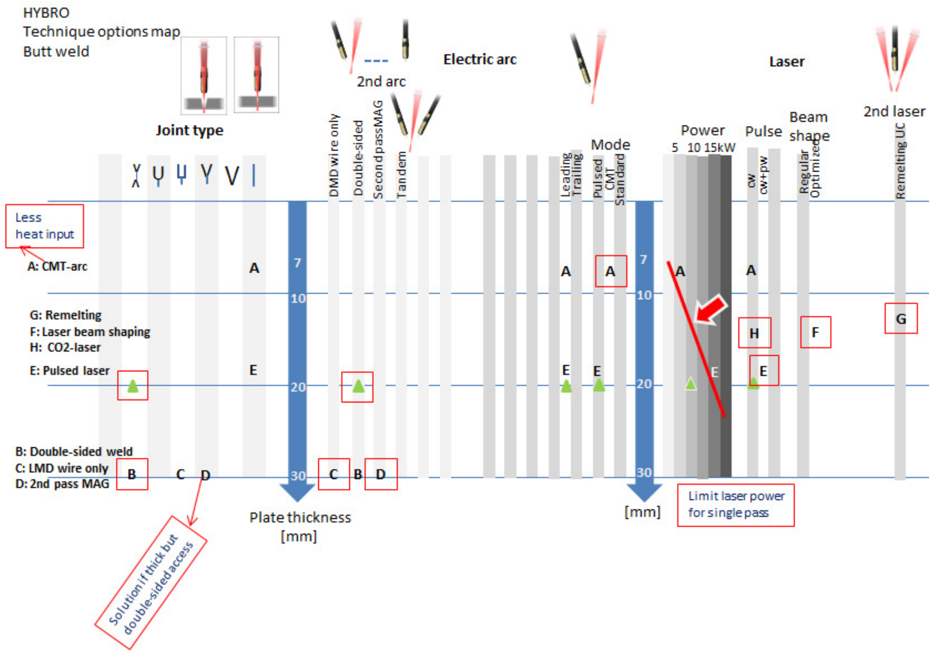

Fig. 4. Technique options map (under evolution) for choice of joint type, laser techniques and arc techniques in laser arc hybrid welding, depending on the plate thickness (butt joint); here techniques A-H, main aspect marked by a red box; comment examples shown.

M2: e-Archive - for electronic material on hybrid welding

As a rational main step of the mapping, an e-archive for electronic material on laser arc hybrid welding was accomplished, here in frame of the project HYBRO. Electronic material was divided into sample parameters, weld cross section photos, top bead photos, root photos, videos / high speed, gap scans, photos, defect photos; an according legend was created. As the two highest levels of hierarchy the joint type and the plate/weld thickness were chosen. Figure 5 shows the actual navigation map for the e-archive while Fig. 6 shows examples of entries of electronic material. All samples are numbered in a consecutive manner. For example for a thickness of 18 mm, 12 sample parameters are available, numbered #440-451, 14 cross section photos, 20 top bead appearance photos and 11 high speed videos are stored in the archive, named accordingly, all in a folder called B18 (Butt joint, 18 mm). Totally, so far parameters on 546 hybrid welds are contained in the archive (including welds of non-acceptable quality), 167 cross section photos and 111 high speed imaging videos can be found. These numbers give the user a first survey on the amount and type of electronic material accessible in the archive. One important feature of such an e-archive is that it can be very quickly extended by new material, simply by copying new electronic material into the corresponding folder and renaming it accordingly. No software (e.g. database) or software skills are needed. The material can be easily copied or located for wider access. Examples of entries of electronic material are shown in Fig. 6.

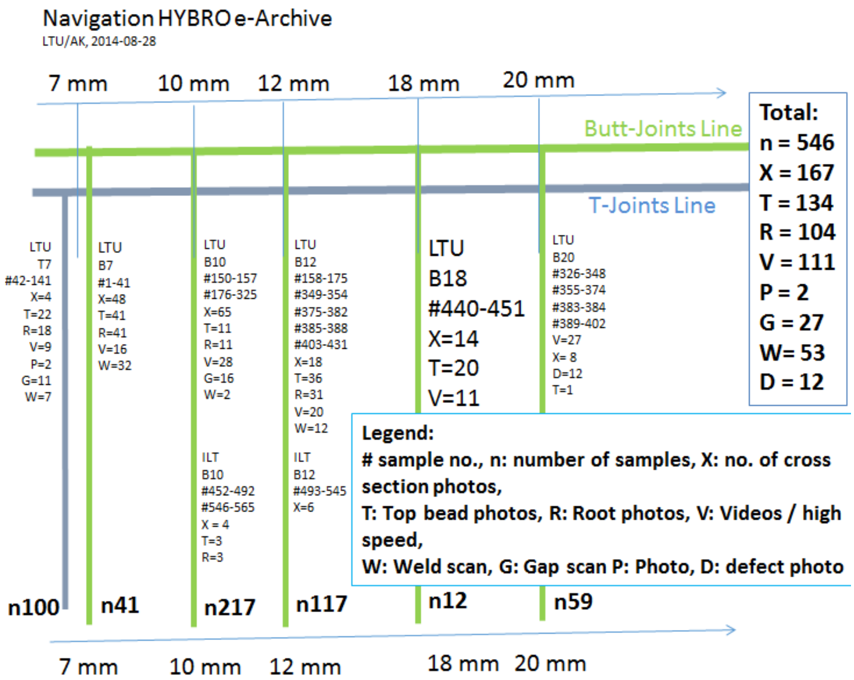

Fig. 5. Survey map for the e-archive of data/e-material on hybrid welding in the project HYBRO; subway-system guiding to the respective joint type and weld throat thickness, then showing the number of respective available data/e-material of different type (see Legend).

A database contains process parameters and first judgments of results (colour scheme), the folder hierarchy guides to the respective material, joint, thickness and finally type of material. In the respective folder the corresponding number of weld cross sections or high speed imaging video clips can be found, see Fig. 6(a)-(d). Typical entries are macrographs or scans of the weld topology, weld cross section photos, high speed images or FE-simulation results, see Fig. 6(e)-(j). The files follow a consecutive numbering and a systematic file name labelling.

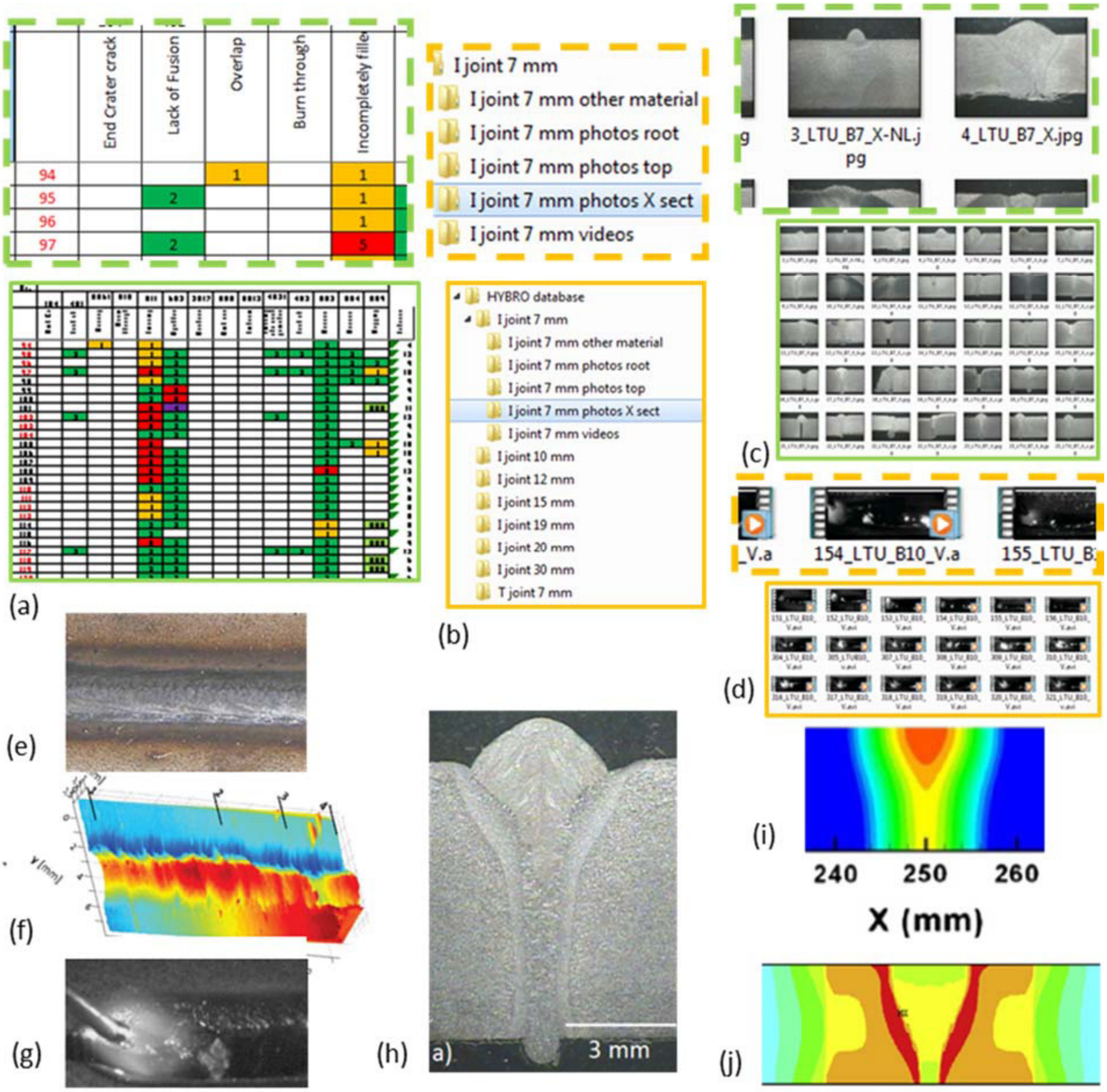

Fig. 6. Typical material stored in the e-archive: (a) process parameter database, including coloured weld quality judgements, (b) folder hierarchy, (c) weld cross sections in one folder of the e-archive, (d) high speed imaging videos, (e) example of a hybrid weld surface appearance photo, (f) scan of a hybrid weld topology, (g) high speed image, (h) weld cross section photo, (i) FE-simulation of the temperature field (cross section; map extension by Chosun University, Korea), (j) FE-simulation of the induced residual stress field (Chosun U).

While this is pure material, also more sophisticated information or knowledge can be arranged and entered. Examples are given in Fig. 7. Figure 7(a) shows a systematic scheme of undercuts in laser arc hybrid welding, including categorization as well as comments on the origin and mechanisms of the undercuts. Figure 7(b) shows a rule to avoid a weld imperfection, here to avoid undercuts that even involve lack of fusion. The undercuts and lack of fusion evolve from the mill scale (oxide layer) at the steel surface, as delivered, and removal of the mill scale beside the joint edges suppresses the formation of this kind of undercuts. In Figure 7(c) the dependence of the weld width variation on arc voltage and laser power was calculated from Meta-Modelling and Design-of-Experiments (DoE), which based on a number of experimental results guides to a theoretical minimum variation of the weld width (weld stability). Figure 7(d) shows corresponding hybrid weld surface appearances, arranged as a map. In contrast to Fig. 6, this kind of material has in common the additional processing and judgment by experts, with the advantage of additional information but the disadvantage of subjective treatment and loss of pure information. So both kinds of entries are valuable in their respective manner.

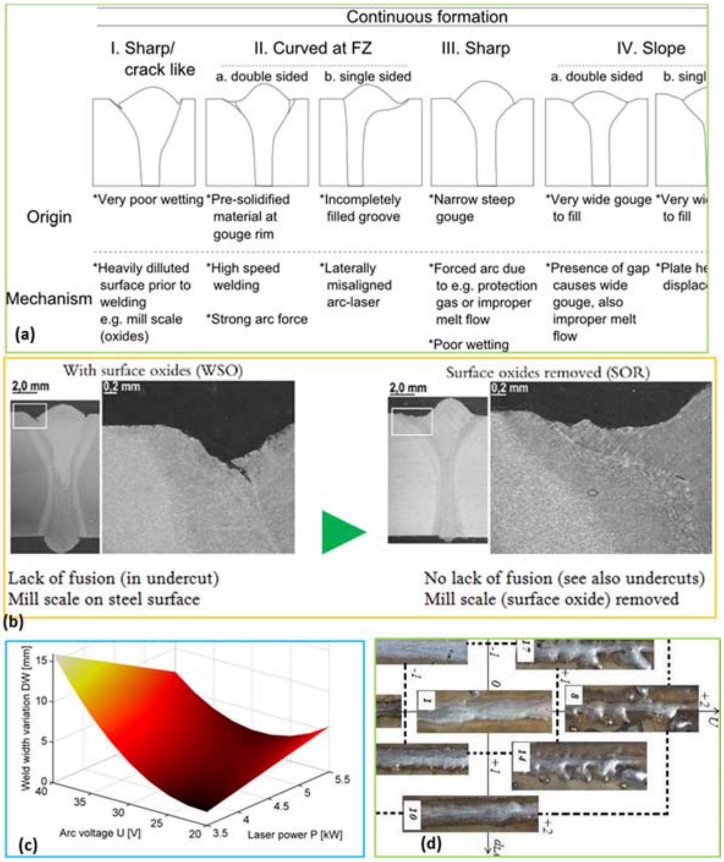

Fig. 7. Typical material processed by an expert before stored in the e-archive: (a) systematics of undercuts in laser arc hybrid welding, including comments, (b) rule to avoid a weld imperfection, here undercuts from the mill scale, (c) meta-model (DoE), here weld width variation (stability) as a function of arc voltage and laser power, (d) map of hybrid weld surface appearances.

It can be summarized that the purpose of the e-archive is to very quickly store, navigate and retrieve electronic material on hybrid welding. A necessary prerequisite was to define the preferred standard format and hierarchy, and to decide practical aspects like accessibility rights. Hence the *e-Archive* has the advantage for easy, quick extension, general applicability and quick first order search, while a disadvantage is the plain, uncommented and unprocessed content.

M3: Defect suppression catalogue

The Defect suppression catalogue collects rules that were identified, usually during experimental parameter variation, on how to improve the weld quality. One example is shown in Fig. 7(b). Lack of fusion in the weld undercut has proven to take place if the steel plate has a mill scale. As explained by Karlsson et al. (2011 II), oxides form that change the melt flow behaviour and the solidification, causing lack of fusion appearing like a crack, as part of a deeper, sharp weld undercut. When removing the mill scale, the melt wets and solidifies well, enabling proper fusion and also reducing the depth of the undercut significantly. The catalogue shows the evidence of the rule and refers to the above publication where the experimental details and even deeper analysis and theoretical explanations can be found. The rule itself remains simple and can therefore be easily applied for any other application where the same imperfection takes place and needs to be suppressed, though without guarantee (limit of validity). Such catalogue can rapidly grow and confirmation of rules can lead to increasing confidence or wider range (or higher likelihood) of applicability of the rule. In 2D-parameter maps the rules can basically be entered, for visualization. One example is Fig. 7(d) where nine different weld surface appearances are placed in a map, showing how parameter variations lead to a more stable weld, see Moradi et al. (2013). The appearance becomes more versatile but the rules are less clearly specified. Figure 7(a) shows a systematic categorization of undercuts in laser-arc hybrid welding and their origins (i.e. the base for rules) as well as theoretical explanations, see Frostevarg et al. (2014).

The *Defect suppression catalogue* has the advantage of advice that can be directly applied at the system to try to improve the quality; disadvantages are lack of generalizing validity of the rules, lack of guidelines when rules need to be combined, and lack of a graphical survey.

M4: MetaModel map

A MetaModel map derived from the DoE study to which Fig. 7(d) belongs is shown in Fig. 7(c), namely the weld width variation (as a measure for the weld stability) as a function of the arc voltage and laser power in laser-arc hybrid welding, Moradi et al (2013, 2014). The surface of the mathematical equation was derived from 17 experimental data points, including the nine results in Fig. 7(c). A distinct valley of minimum variation can be seen, which is desirable, i.e. an optimum relation between arc voltage and laser power exists (with respect to this quality criterion, and for all other parameters at a certain value). On both sides from this valley a clear rule for increasing variation can be derived. The strength of a MetaModel map is obvious; rules and optima can be rapidly identified, for a wide range of parameters. However, the level of uncertainty is high. Moreover, rules have to be put in context to other quality criteria to be optimized simultaneously.

With respect to generalization versus limitation of validity of entries, being a main challenge as mentioned above, the methods contribute in different manners. For the Technique options M1, their general applicability and preferences require growing and generalizing comments to compare the pros and cons for a respective case, particularly for a given joint type, material and sheet thickness. The e-Archive M2 simply needs to grow to cover wider domains of available parameter and result data, but will remain limited with respect to generalization, due to lack of analysis. The Defect suppression catalogue M3 requires a growing number of entries to confirm rules, both by the plain number of confirming (or contradicting !) rules and by the quantitative parameter domains addressed that either widen the confirmed domain of a rule or claim their limits, gradually making the domain boundary sharper. The MetaModel M4 vice versa starts at a generalized level that needs to be validated by additional data and then refined, if necessary. Massive use of a mapping method would rapidly increase the number of entries and could rapidly lead to well explored safe domains of process knowledge. Therefore simply initiating the massive common use of mapping would be highly valuable.

4. Conclusions

(i) More systematic mapping of available material and information is desirable and has high potential. Early decisions on the map standard are important, particularly its hierarchy and the trade-off between realistic material administration and desirable map functions. Further issues are access rights and limits of validity for generalizing knowledge.

(ii) Maps to guide towards favourable hybrid welding techniques have been developed, accompanied by comments, particularly on the pros and cons of each technique. The *Technique options map*, Method M1, has the advantage of providing a graphical survey on different technique options but a disadvantage is the subjective and limited comments entered while generalization of preferences can be difficult.

(iii) A systematic *e-Archive*, M2, has been established, containing electronic material, like weld cross sections or high speed images, as well as by more sophisticated information, like rules to suppress weld imperfections. The *e-Archive*, M2, has the advantage for easy, quick extension, general applicability and quick first order search, while a disadvantage is the plain, uncommented and unprocessed content.

(iv) The *Defect suppression catalogue*, M3, has the advantage of advice that can be directly applied at the system to try to improve the quality; disadvantages are lack of generalizing validity of the rules, lack of guidelines when rules need to be combined, and lack of a graphical survey.

(v) The *MetaModel*, M4, has the advantage of generally applicable rules and quantitative operating point recommendations and visualization of the content, including partial explanations, while the main disadvantage is an often high level of uncertainty of the wide validity of data and rules.

(vi) An incorporation of the above four methods can combine their advantages. The data require standardized formats, to be defined and consequently followed. M4 will require a commercial or in-house software code while M1-M3 can be handled without commercial codes.

(vii) A basic issue are accessibility and IPR rights for which filtered electronic versions can be imagined, with access to different extents or domains of data/entries depending on the user and on chosen price/secrecy levels. Users could develop their maps further, with own security levels. Full open access entries, e.g. provided by universities would be desirable, too.

(viii) It can be expected that suitable mapping, either regionally or globally, protected or public, can lead to faster and better optimization of the hybrid welding process.

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